REMR TECHNICAL NOTE HY-N-1.5

SCOUR PROTECTION DOWNSTREAM OF UNCONTROLLED FIXED-CREST DAMS

PURPOSE: To provide guidance for developing a scour protection plan for an existing uncontrolled fixed-crest dam.

BACKGROUND: Scour has occurred downstream from many of the Corps of Engineers uncontrolled fixed-crest dams that serve to provide a navigation pool. Many of these structures were designed and constructed more than four decades ago and most of them will be required to operate for several more years. Physical model studies have been used to develop scour protection plans to protect the area immediately downstream from the dam's spillway apron from scour caused by the hydraulic flow conditions for various Corps projects. The geotechnical properties of the foundation and streambed were not addressed in these model studies.

TYPES OF FIXED-CREST DAMS: The uncontrolled fixed-crest dams model-tested were grouped into three categories based on the geometry of the structure (Figure 1) for this discussion. The Type 1 structure can be described as a large dam with smooth upstream and downstream corners on the crest, the vertical distance (elevation change) between the crest and the spillway apron between 30 and 50 ft, and a short spillway apron. The Type 2 can be described as a small dam with smooth upstream and downstream corners on the crest, the elevation change between crest and spillway apron between 10 and 20 ft, and a short spillway apron. The Type 3 structure can be described as a small blocky dam with chamfered upstream and downstream corners on the crest, an elevation change between the crest and spillway apron between 5 and 10 ft, and a short spillway apron.

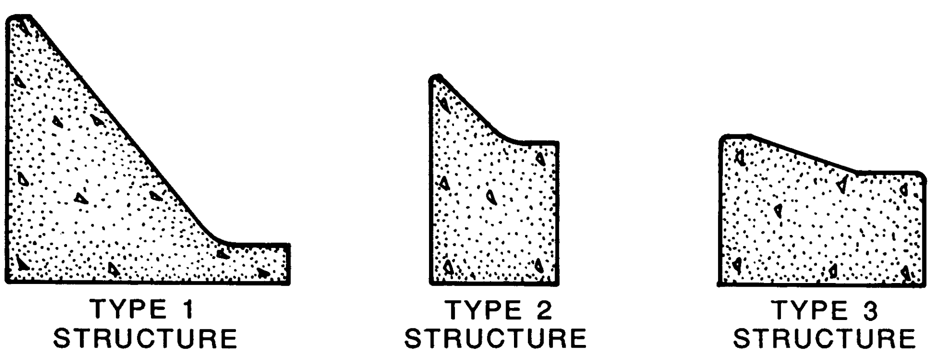
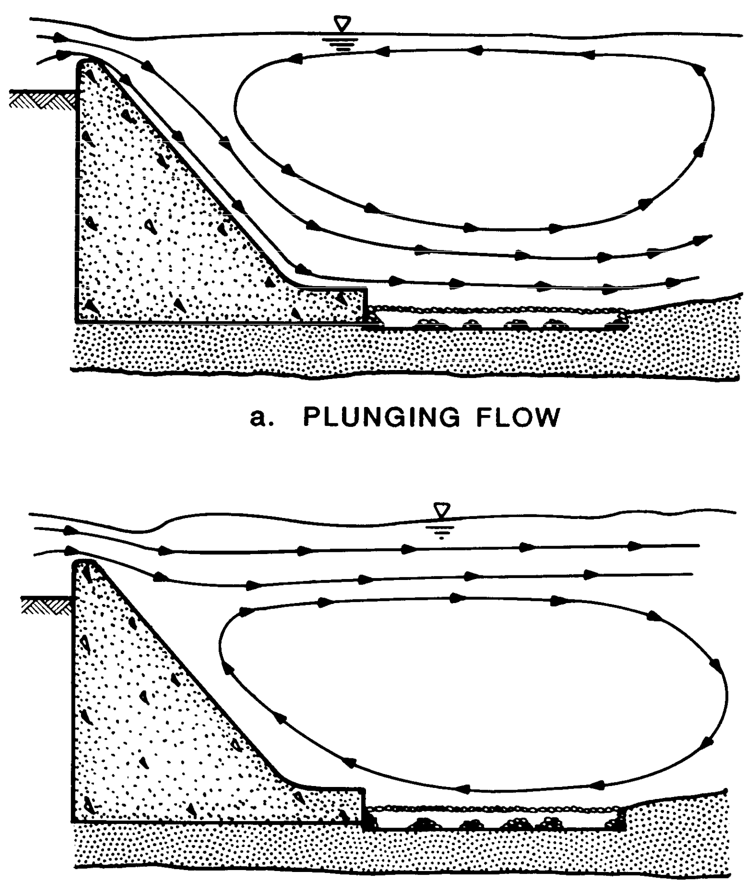


Figure 1. Uncontrolled Fixed-Crest Dams

MODEL TESTS RESULTS: Observations of the various flow conditions revealed that the worst attack on the streambed generally occurred during a flow transition from one regime to another. Plunging flow was considered one regime and riding flow the other. Plunging flow occurs when the trajectory of the flow jet issued from the upper pool travels in a downward direction usually adhering to the face of the spillway. Plunging flow is not dominated by the tailwater and is generally considered to be free, uncontrolled flow. However, some model data have indicated that the tailwater can effect plunging flow conditions. Riding flow occurs when the tailwater increases and causes the flow jet to remain near the water surface. Riding flow is generally considered to be submerged, uncontrolled flow.

During the transition from plunging to riding flow and back again, turbulence capable of displacing large stones occurs over the streambed below the dam. This flow transition is effected primarily by discharge, tailwater elevation, and geometry of the structure which are all usually unique to a particular project. Also, the duration of the transition flow varies from one project to the next. Scour measurements obtained after the event probably do not reflect the degree of scour that was present during the peak of the flow event. The scour hole downstream of a dam was probably larger during the transition flow than when the survey was conducted after the event was over.

a. <u>Type 1 Structure.</u> Flow conditions associated with the type 1 structure are shown in Figure 2. During plunging flows (Figure 2a), velocities frequently near 20 ft/sec were measured at the end of the spillway apron. This high velocity flow jet causes



a. PLUNGING FLOW

b. RIDING FLOW

Figure 2. Flow Conditions With Type 1 Structure

intense turbulence and pressure fluctuations downstream from the end of the spillway apron and is capable of displacing conventional riprap even with low and intermediate discharges. Using existing riprap design guidance and considering 20 ft/sec as the average velocity (since this is the velocity near the stone protection), a d_{50} size stone of 5.0 ft is suggested. This compares with model results obtained from the type 1 structures when the stones were offset below the apron elevation and placed on a 1V on 3H downward slope. In some model tests, large stones were displaced when placed as a horizontal blanket below the spillway apron. The tailwater elevations of type 1 structures model tested were considered high, 2.2 to 2.4 d_2 (see definition sketch in Figure 3), and previous researchers have shown that the higher the tailwater with the same unit discharge the less scour will occur downstream from a flat apron (Ref a).

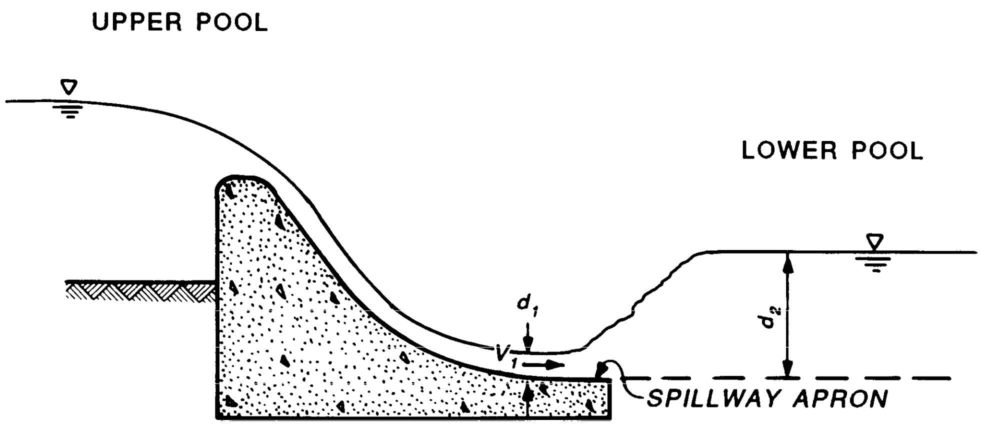
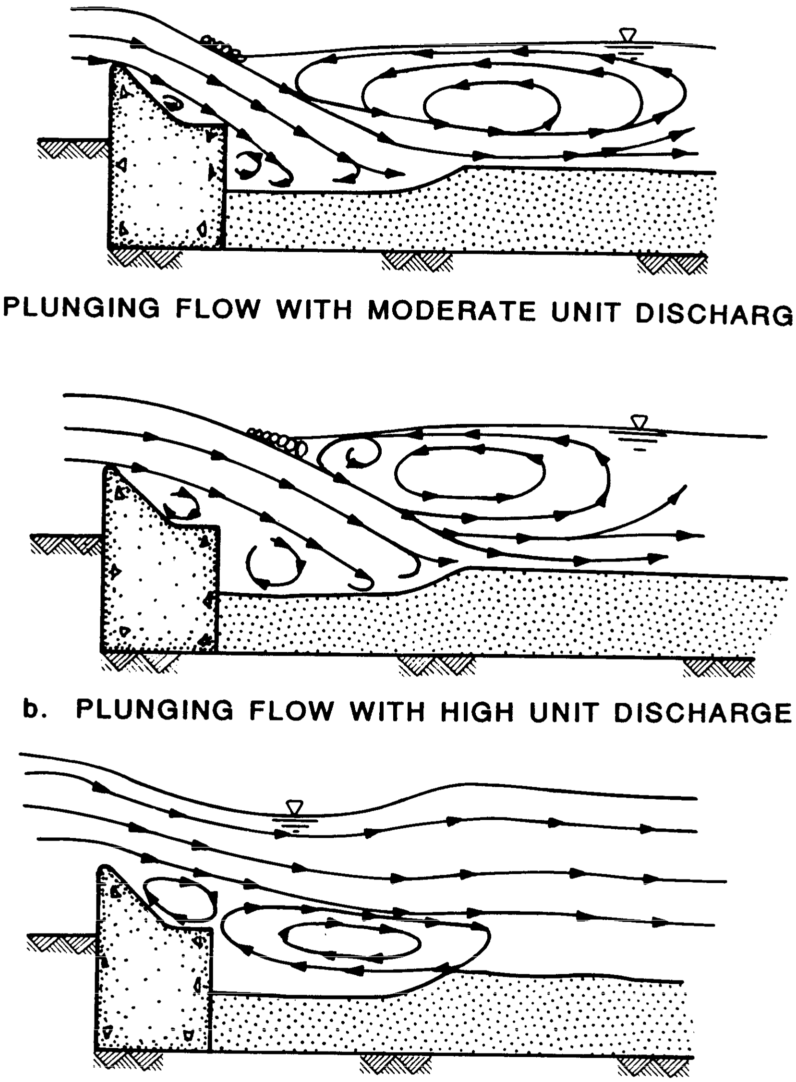


Figure 3. Definition Sketch for Theoretical Hydraulic Conditions

Soundings taken downstream from type 1 structures have indicated that scour was evident downstream from the apron, probably due to the short spillway apron. Model tests indicated that an end sill equal in height to $d_2/6$ is beneficial for the type 1 structure and is more effective when the ratio of d_1/apron length (d_1/L) is low (less than 0.1). The addition of an end sill may cause a slight increase in surface waves for some discharges which should be considered for navigation purposes. Once the flow transitions to a riding flow jet, the attack on the area downstream from the spillway is reduced significantly and flow in this area is in an upstream direction as illustrated in Figure 2b.

b. Type 2 Structure. Plunging and riding flow conditions with the type 2 structure are shown in Figure 4. This structure exhibits the same characteristic plunging flow conditions as the type 1 structure for lower-unit discharges, but conditions shown in Figures 4a and 4b occur with higher-unit discharges. As the discharge increases, the flow begins to plunge farther and farther downstream from the structure, severely attacking the area below the dam. Scour protection usually requires structural modifications to improve energy dissipation and reduce scour potential.



a. PLUNGING FLOW WITH MODERATE UNIT DISCHARGE

b. PLUNGING FLOW WITH HIGH UNIT DISCHARGE

c. RIDING FLOW

Figure 4. Flow Conditions With Type 2 Structure

Consideration should be given to designing a spillway extension that will provide a total apron length of at least $3d_2$ for the maximum plunging flow condition. Research has shown that the longer the apron length provided for the same flow conditions, the less scour will occur downstream from the apron (Ref b). Also an end sill located at the end of the spillway equal in height to $d_2/6$ will deflect the high velocity flow from the area below the extension.

Various techniques such as driving sheetpile cutoff walls downstream from the end of the original basin and backfilling with riprap and grouting or using barges filled with grouted rock have been considered for spillway extensions. Model results of the type 2 structures indicated that even with the spillway extension, rock 4 and 5 ft in diameter was required immediately downstream due to the turbulence associated with the maximum plunging flow.

c. <u>Type 3 Structure.</u> Flow conditions with the type 3 structure are shown in Figure 5. This structure is more like an obstruction in

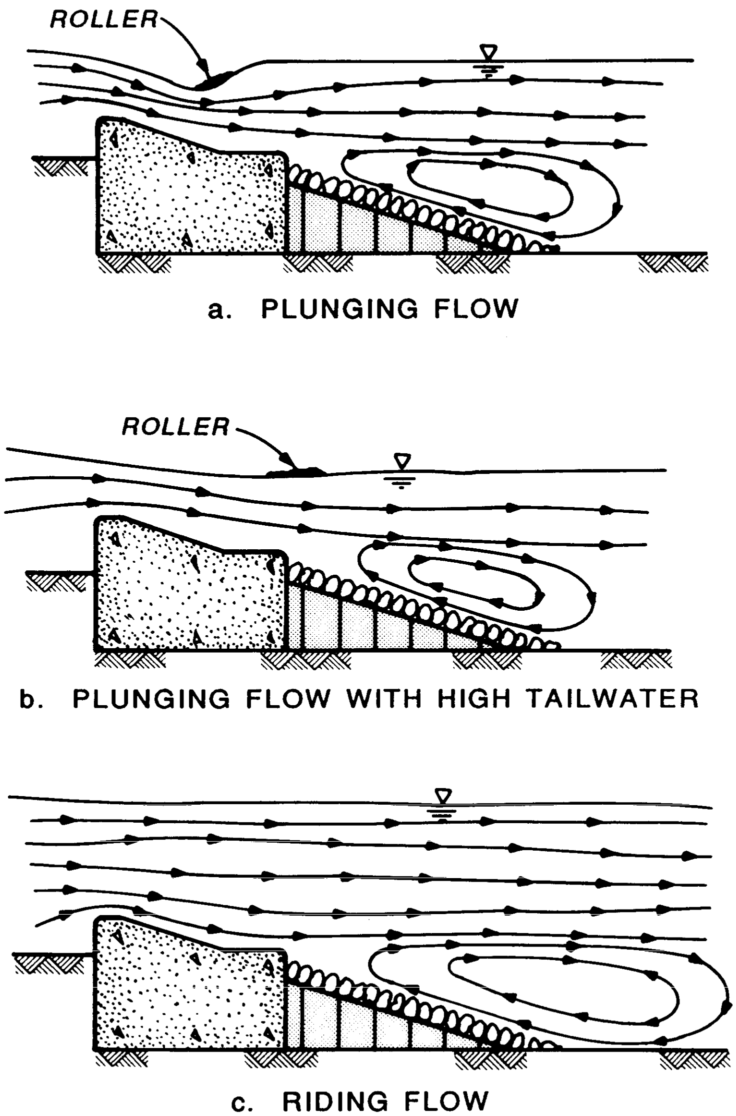


Figure 5. Flow Conditions With Type 3 Structure

the flow rather than a hydraulically desirable structure. The distinction between plunging and riding flow is not as obvious with this type structure as with the other two. The flow was considered to be plunging when a hydraulic roller was observed over the spillway or spillway apron. Figure 5 shows a type 3 structure with the same unit discharge for three different tailwater conditions.

The flow over the streambed immediately downstream from the spillway apron is in an upstream direction for all three conditions. This allows stone protection to be used effectively when offset below the apron and sloped downward away from the dam. Tailwaters less than d_2 might cause the flow to plunge directly below the dam and require scour protection more substantial than riprap or large stones. The Type 3 structure model tested had tailwaters of approximately $1.2d_2$ and 4- to 5-ft-diameter stones offset below the apron and sloped downward provided adequate protection. The short spillway apron is considered to be the reason for the existing scour downstream from these structures.

DESIGN GUIDANCE:

a. Type 1 and 2 Structures. Figure 6 is a definition sketch showing the parameters of interest.

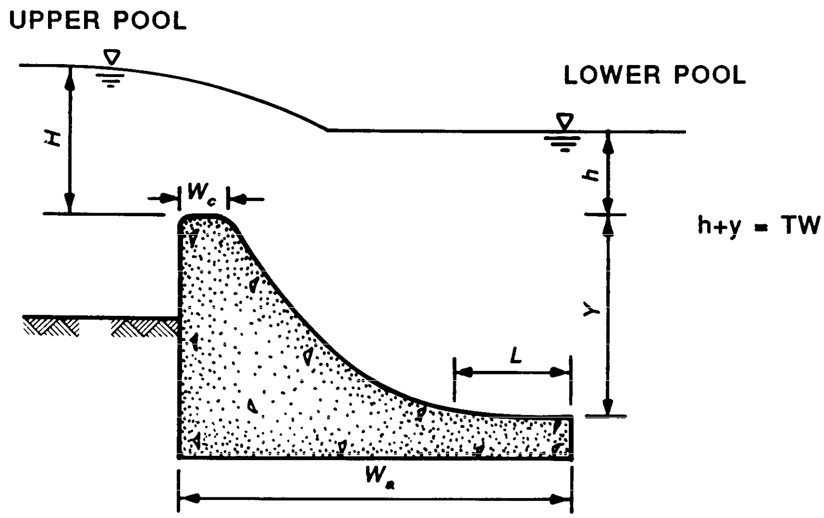


Figure 6. Definition Sketch for Existing Project Conditions

The following procedure is provided to assist in developing a scour protection plan.

1. Using the upper and lower pool rating curves for the project, determines the discharge that gives an h/H value of 0.7.

2. Divide this value by the weir length to determine the unit discharge.

3. Determine the theoretical hydraulic parameters d_1, v_1, F_1, and d_2 for the project as follows:

   To compute d_1 and v_1, it is assumed that there is no energy loss between the upper pool and the spillway apron. The energy equation is used to determine the entering depth and velocity into the spillway apron according to

$$\text{Upper pool elevation} + \text{Velocity head upstream} = \text{Spillway apron elevation} + \frac{v_1^2}{2g} = d_1$$

Knowing the upper pool elevation, velocity head upstream (if significant), and discharge, v_1 and d_1 can be solved by trial and error. Next, the Froude number of flow entering the spillway apron is computed according to

$$F_1 = \frac{v_1}{\sqrt{gd_1}}$$

Then the momentum equation is used to determine the ratio between the depths before and after the hydraulic jump according to

$$\frac{d_2}{d_1} = 0.5(\sqrt{1 + 8F_1^{\,2}} - 1)$$

A definition sketch is shown in Figure 3.

4. Knowing d_1 and d_2, the parameters d_1/L and TW/d_2, where L is the length of the spillway apron and TW is the tailwater depth above the spillway apron for the discharge determined in step 1, can be determined for the project.

5. Enter plot shown in Figure 7 with d_1/L and TW/d_2 to determine scour potential caused by hydraulic flow conditions for this project.

   Figure 7 is beneficial in evaluating the degree of scour protection needed for an existing project. It was developed based on a very limited amount of model and prototype data, but the general approach is a logical one and agrees with accepted hydraulic practices. The logic considers that a large value of d_1/L is not desirable and will probably result in high scour potential. Values of d_1/L less than 0.1 are desirable and the lower the ratio the better. The logic also considers that values of TW/d_2 less than 1.0 are not desirable for a spillway apron with no baffle blocks or end sill to aid in energy dissipation. The higher the value of TW/d_2 for a constant d_1/L, the less scour potential exists. The dividing zones among the areas of scour potential are not exact.

   A survey of the existing conditions below the project is also needed to determine the extent of the scour protection required. Large scour holes indicate the energy of the flow is being dissipated downstream from the dam. Scour holes progressively enlarging indicate flow conditions that have high or moderate scour potential occur frequently and the streambed is an erosive material. This dam will need a structural modification. If the soundings indicate slight scour and the hydraulic flow conditions indicate high or moderate scour potential, and these conditions are experienced frequently, the streambed is probably an erosion resistant material.

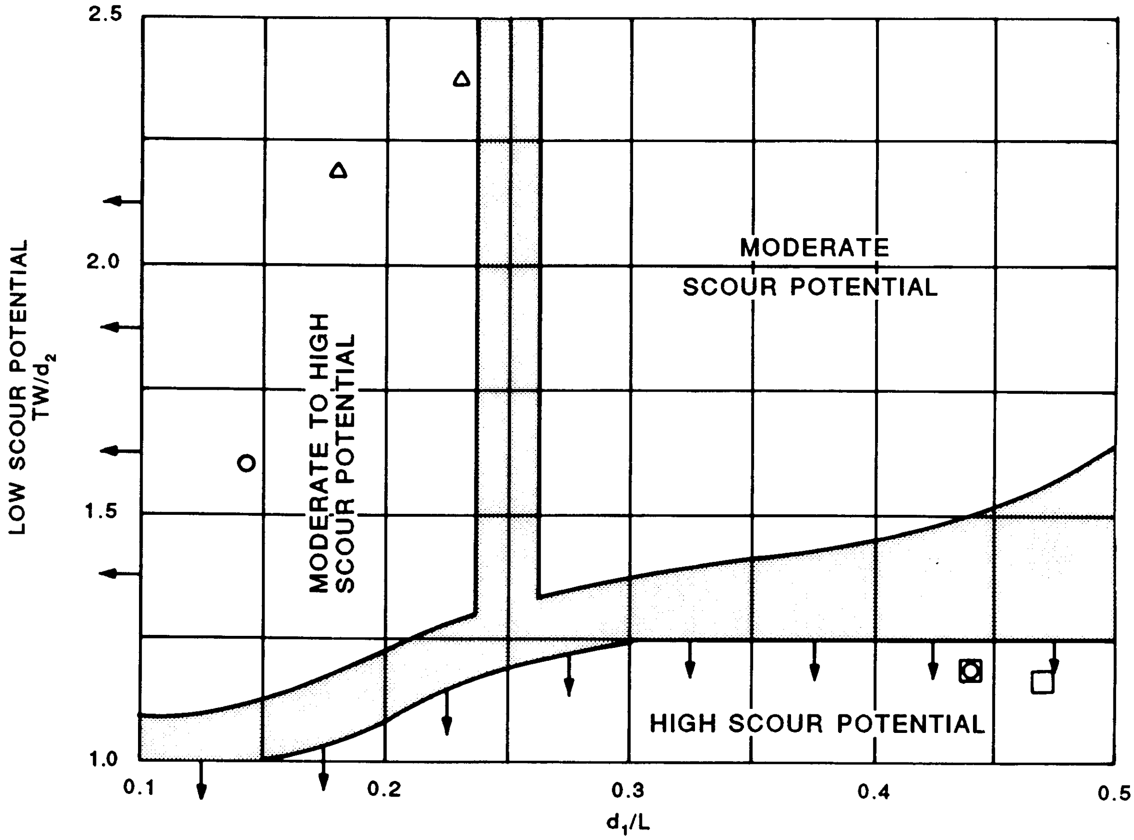


Figure 7. Scour Potential Based on Hydraulic Flow Conditions

Structures similar in shape to the type 1 structures with ratios of TW/d_2 greater than 1.0 and d_1/L less than 0.1 can probably be repaired using large stone protection. Those with low TW/d_2 ratios and high d_1/L ratios will probably require one or more structural modifications such as a secondary stilling basin, end sill, or spillway extension. Structures similar to the type 2 structures frequently having unit discharges greater than 100 cfs and ratios of d_1/L greater than 0.1 are likely to have large scour holes below them if the streambed consists of an erosive material. Minimal scour below a structure of this type probably indicates a fairly competent material. A structural modification as mentioned above will probably be a necessity for these structures.

b. Type 3 Structures. It is difficult to generalize results for the type 3 structure due to the unusual flow conditions that occur. The flow over the stone protection was in an upstream direction for the structures model tested. This was primarily due to the presence of a large scour hole downstream from the spillway apron. Flow conditions for a structure of this type will be different if a scour hole does not exist below them and therefore generalization of these results is not attempted. A model study is recommended, but if it cannot be conducted, the upstream slope of the existing scour hole could be armored with a moderate size stone

(2-4 ft) offset below the top of the apron and monitored to determine its stability. The scour protection developed from model studies of the types 1, 2, and 3 structures are based on hydraulic flow conditions and do not consider structural and geotechnical aspects.

CONCLUSIONS: Uncontrolled fixed-crest dams, similar in design to type 1 and 2 structures, that experience large discharges annually with scour holes downstream that are progressively enlarging should be considered for structural modifications. Structural modifications might include the addition of an end sill, lengthening the existing spillway apron, constructing a secondary stilling basin, or a combination of these. Structures that have existing scour holes that are not noticeably enlarging could be modified with the use of large riprap, derrick stone, or large grout-filled fabric bags, if these materials can be offset sufficiently below the spillway apron (at least 2 ft) to avoid the high velocity jet exiting the spillway apron. These materials function to armor the upstream slope of the existing scour hole and should be placed on slopes that approximate a 1V on 3H. Already undermined structures are an indication that turbulent flow conditions occur below the dam, and that riprap, derrick stone, or large grout-filled fabric bags may not provide adequate protection. Insufficient tailwater can contribute to scour and steps to increase the depth of tailwater should be taken. Properly designed filters (preferably graded granular filters) should be incorporated into the scour protection chosen to insure a functional product. Information regarding the recommended scour protection plans developed from the model studies can be found in REMR Technical Note HY-N-1.3.

REFERENCES:
a. Farhoudi, J. and Smith, K., 1985. "Local Scour Profiles Downstream of Hydraulic Jump," Journal of Hydraulic Research, Vol 23, No. 4.

b. Hassan, N. and Rangaswami, N., 1985 (Nov). "Local Scour Downstream of an Apron," ASCE Journal of Hydraulic Engineering, Vol 111, No. 11.